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Specification and Drawings, as originally filed, with Application for Patent Serial No: **2,449,551**, on November 17, 2003, by **PHOTON CONTROL INC.**, assignee of Ivan Melnik, for "Optical Device and Method for Sensing Multiphase Flow".

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OPTICAL DEVICE AND METHOD FOR SENSING MULTIPHASE FLOW

Technical Field

5 **[0001]** The present invention relates to optical flow meters for sensing the velocity of fluids, including mixtures of gaseous and liquid fractions such as steam, moving in a pipe.

Background

10 **[0002]** The need for measurement of the velocity and flow rate of steam, for example, is a known problem in industrial control because steam is widely used as an energy carrier in many processes and because measurement of steam flow is a complicated task. The main reason for this complication is the presence of two fractions in the flow, 15 a gaseous or vapour phase which is mixed with a liquid phase (water). The liquid phase moves in the pipe in the form of water droplets of various sizes, fluctuating water aggregates and water condensate which collects in the bottom of the pipe if quality of steam is low. Each of the components moves with different speed. The proportion between these 20 components varies in time, water aggregates can combine together and water condensate can suddenly be picked up and be accelerated by the flow creating a "hummer effect." In addition, the quality of steam changes along the pipe depending on the temperature outside of the pipe, pipe insulation, pipe bending, etc. All these factors make steam 25 flow complicated for measurement.

[0003] A number of solutions have been proposed for measuring steam flow. Some are based on tracing the electrical properties of steam and water by means of measuring capacitance of the fluid at 30 several points along the pipe or by tracking the variation of fluid density with ultrasound. The main drawback of these methods is high inconsistency with operating temperature. High-power industrial boilers run at temperatures higher than 350°C which are beyond the limit of capaci-

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tive and ultrasonic methods. Other solutions based on gamma-irradia-
tion methods could be applicable for steam measurement; however,
gamma-irradiation is expensive and it creates a risk for operating
personnel.

5

[0004]   Cross-correlation methods for non-invasive measurement of
fluid flow using optical means are known in the art. Optical methods
usually are not adversely affected by high temperature because light
sources and photodetectors can be located remotely from the hot mea-
10   suring zones. U.S. Patent No. 6,611,319 (Wang) describes an optical
flow meter which is based on registration of the light twinkled (scintil-
lated) due to the small changes of the refractive index with changes in
temperature. The moving fluid is transilluminated by a single light
source and the direct light is measured by two photodetectors spaced
15   apart along the direction of flow. A cross-correlation function between
signals from those photodetectors is calculated and a position of its
maximum is determined. This position provides the average time which
is necessary for the flow to move from one photodetector to the other.
Consequently, the ratio of the distance between the photodetectors to the
20   time delay gives an estimate of the average velocity of the flow.

[0005]   A similar correlation technique has been described in WO
02/077578A1 (Hyde) for measuring gas flow in large pipes using
attenuation of the light by the gas stream. Different constituents in the
25   moving gas may have different absorption in the infrared region, which
will cause modulation of the light passing through the pipe.

[0006]   However, both scintillating method of Wang and the
infrared absorption method of Hyde require long optical paths in order
30   to accumulate enough abnormalities in the flow. Such methods require
minimum pipe diameter of about one meter in order to perform reliable

flow measurements. Diameters such as these are too big for steam
pipelines where maximum diameter is 12 inches (30cm) and most pipe
sizes are from 2 inches (5cm) to 6 inches (15cm). In addition, the
highly divergent light beam from the single light source used in the

5   scintillating method of Wang spreads the time delay because different
portions of the fluctuated flow cross the beam at different locations.
This reduces the accuracy of the measurement. Collimated beams used
in the infrared absorption method of Hyde are not affected by this
effect, but steam does not absorb much light. High quality steam, in

10   particular, is highly transparent over a wide range of wavelengths.
Unscattered light, therefore, has a very low modulation depth due to the
high intensity of direct light from the light source. In addition, none of
the optical methods described above have been applied for sensing the
quality of steam, which is of the same importance as velocity and flow

15   measurement.

[0007]   Therefore, there is a need for an apparatus and method for
sensing the flow velocity of mixtures of gas and liquid such as occurs,
for example, for steam moving in small pipes.

20

Summary of Invention
[0008]   An object of the present invention is to provide an optical
device and a method for sensing steam flow in industrial pipes.

25   [0009]   It is another object of the invention to provide such an
optical device and a method that will be suitable for steam of varying
quality.

[0010]   It is a further object of the invention to provide such an
30   optical device and a method that may simultaneously sense the quality of
steam.

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[0011]   According to a preferred embodiment of the present inven-
tion, two or more narrow collimated beams of light are directed towards
a fluid flowing within in a pipe through transparent windows in the

5   walls of the pipe. The beams are spaced apart along the direction of the
flow. Liquid droplets and other flow components which are moving
through the pipe cross the beams and scatter and deflect the light.
Scattered and deflected light passes through transparent windows in the
opposite side of the pipe and is focused by a collecting optical system

10   into photodetectors. Unscattered light may be collected by another
optical system for monitoring purposes and for absorption measurement
if the quality of the steam is low.

[0012]   In one embodiment, signals from the photodetectors are

15   digitized and separated into different groups by filtering them with
digital band-pass filters. The groups are associated with different steam
components such as, for example, miniature, medium, and large drop-
lets, and water aggregates. The differentiation is based on frequency
bandwidths; lower frequencies correspond to larger droplets and higher

20   frequencies correspond to smaller droplets. Cross-correlation functions
are calculated for each group and time delays between signals from
spaced apart beams are determined. The average velocity of each steam
component is calculated as a ratio of spacing distance between the
beams over time delay. The local velocity of each steam component is

25   sensed by illuminating the flow with two beams from a variety of
directions and collecting the deflected and scatted light from a variety of
measuring zones across the pipe. According to another embodiment of
the invention, additional vertical beams are delivered through the
horizontally disposed pipe, thus the level of liquid condensate is mea-

30   sured by sensing the light absorption. Flow intensity of each flow
component is determined by calculating dispersion of filtered signals.

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Total flow rate is calculated as the sum of all flow components mea-
sured in all measuring zones across the pipe. Gaseous or vapour frac-
tion is defined as the fastest flow fraction moving in the pipe.

5   [0013]   According to another embodiment of the invention, there is
provided a method for measuring the velocity of a multiphase fluid
flowing in a pipe. The method comprises the steps of: directing a pair
of collimated beams of light from an illuminator through the multiphase
fluid by means of transparent portions of the pipe, the pair of collimated
10   beams spaced apart in a direction of flow of the multiphase fluid by a
predetermined distance; detecting scattered, deflected and attenuated
light with a pair of photodetectors to produce a pair of signals, each of
the pair of photodetectors associated with one of the pair of collimated
beams; calculating a cross-correlation function between the pair of
15   signals to determine a time delay between the signals; and, calculating
the average velocity of the multiphase fluid by taking the ratio of the
predetermined distance to the time delay.

[0014]   The described optical device and method are suitable for
20   measuring the multiphase flow such as steam in a small pipe and
provide qualitative analysis of the moving media, such as steam quality.
The method is highly sensitive because it detects microscopic water
droplets in high quality steam as well as large water droplets and water
aggregates in low quality steam.
25

[0015]   In this specification, water and steam measurement are
referenced, but the invention applies equally to all transparent liquids
and their corresponding gases. The invention can be applied to mixtures
of water and hydrocarbons such as, for example, natural gas moving in
30   a pipe. Sensing is provided by calculation of cross-correlation between
signals from a number of photodetectors disposed along the pipe, which

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register light scattered by the gaseous fraction and deflected and absorbed by the liquid fraction.

[0016] The present invention as well as its numerous advantages
5 will be better understood by the following nonrestrictive description of possible embodiments made in reference to the appended drawings.

Brief Description of Drawings

[0017] In drawings which illustrate non-limiting embodiments of
10 the invention:

Figure 1 is a schematic representation of an apparatus for sensing multiphase flow according to one embodiment of the invention;

Figure 2 is a schematic representation a portion of an optical system suitable for use with the apparatus of Figure 1;
15 Figure 3A is an example of signal detected by a photodetector indicating the presence of miniature and large size water droplets;

Figure 3B is an example of signal detected by a photodetector indicating the presence of medium size water droplets and water aggregates;
20 Figure 4A is a schematic representation of signals from two photodetectors indicating a temporal shift caused by the displacement of the light beams along the flow;

Figure 4B is an illustration of the cross-correlation function between the two signals of Figure 4A;
25 Figure 5 is an example of four cross-correlation functions corresponding to four different components in steam flow;

Figure 6 is a schematic representation of an apparatus for sensing multiphase flow employing a vertical two-beam channel for measurement of water condensate according to another embodiment of
30 the invention;

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Figure 7 is a schematic representation of an apparatus for sensing multiphase flow with an additional measuring zone across the pipe, according to another embodiment of the invention;

Figure 8 is a schematic representation of multiple measuring
5   zones across the pipe using multiple optical collecting systems, according to another embodiment of the invention;

Figure 9 is a schematic of a multi-focal coaxial collecting optical system, which collects light from the multiple measuring zones of Figure 8;

10   Figure 10 is a schematic of a multi-focal coaxial collecting optical system, which collects light from the multiple measuring zones of Figure 8, working in back-scattering mode;

Figure 11 is a block diagram illustrating an example of signal processing in a single channel with two photodetectors and multiple
15   band-pass filters; and,

Figure 12 is a block diagram illustrating an example of a calculation of liquid and gas flow rates based on *m* measuring channels and *n* flow components.

20   <u>Description</u>

[0018]   Throughout the following description, specific details are set forth in order to provide a more thorough understanding of the invention. However, the invention may be practiced without these particulars. In other instances, well known elements have not been
25   shown or described in detail to avoid unnecessarily obscuring the invention. Accordingly, the specification and drawings are to be regarded in an illustrative, rather than a restrictive, sense.

[0019]   Figure 1 shows a first embodiment of an optical device for
30   sensing multiphase flow. An illuminator 10 generates two narrow collimated beams of light 12 and 14, which enter a fluid-carrying pipe

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16 through an illuminating window 18. Beams 12 and 14 may comprise
infrared, ultraviolet, or visible light. Beams 12 and 14 are disposed
apart at a distance *d* along the direction of fluid flow. Beams 12 and 14
are scattered, deflected and absorbed by the fluid moving through pipe

5   16. Scattered and deflected light passes through a collecting window 19
at the opposite wall of the pipe. The light passing through collecting
window 19 is collected by an optical system (not shown in Figure 1),
and focused onto a photodetector array 20. Photodetector array 20
preferably comprises photodetectors 20a and 20b positioned to receive

10   scattered and deflected light collected by the optical system under
different angles, so photodetectors 20a and 20b can measure light
scattered and deflected at different degrees from the optical axis of
beams 12 and 14, respectively. Photodetector array 20 preferably also
comprises photodetectors 20c and 20d positioned to receive direct

15   (unscattered) light collected by the optical system, so that photodetectors
20c and 20d can measure the absorption of light from beams 12 and 14,
respectively, by the flow.

[0020]   Figure 2 schematically illustrates a portion of an optical

20   system 22 suitable for use with the embodiment of Figure 1. The
illustrated portion of optical system 22 comprises optical collectors 24
and 26. A liquid droplet 21, moving in the pipe crosses beam 12.
Droplet 21 scatters and deflects a portion of the light in beam 12 in a
manner depending on the ratio of its size to the wavelength of the light

25   and its refractive index. Smaller droplets with sizes comparable to the
wavelength of the light predominantly scatter light in large solid angles,
while larger droplets mostly deflect light in shallow angles. Scattered
and deflected light 23 spreads inside the pipe and a portion of it passes
through window 19 and is focused by optical collector 24 into

30   photodetector 20a. The direct (unscattered, but attentuated) light 27
passes through window 19 and either is eliminated by absorption or is

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focused by optical collector 26 into photodetector 20c. Registering the direct light provides power monitoring of the illuminator 10 and indicates the light attenuation due to absorption by very large water droplets.

5

[0021]   The signals generated by photodetectors according to the invention are typically made up of a plurality of components of different frequencies. Figures 3A and 3B illustrate examples of typical signals from a photodetector, such as photodetector 20a or 20b, registering

10   scattering light within a shallow angle to the optical axis. The graphs of Figures 3A and 3B plot signals from a photodetector (in millivolts) versus time (in seconds x 10^{-4}). The example signals may be separated into a high-frequency component 32, a medium frequency component 34 and a low-frequency component 36, as well an ultra-slow components

15   38 and 39 (solid line), all created by different components of the fluid flow. Components 32, 34 and 36 are created respectively by miniature (size less than 1 micron), medium (size about a micron), a large (size larger than 2 microns) water droplets, and components 38 and 39 are created by water aggregates fluctuating in the pipe.

20

[0022]   The two-beam arrangement shown in Figure 1 leads to a temporal shift of signals. As elements of the fluid flow through pipe 16 they pass through beam 12 before beam 14, and the resultant fluctuations occur in the signal from photodetector 20a before they

25   occur in the signal from photodetector 20b. The shift is schematically shown in Figure 4A for two photodetectors, PD1 and PD2. Photodetectors PD1 and PD2 may comprise any pair of photodetectors which register light from two beams of light separated by the distance d along the direction of the fluid flow. A cross-correlation function

30   between the two signals from PD1 and PD2 will have a maximum at an elapsed time τ (time delay), as illustrated in Figure 4B, defined as

- 10 -

$$\tau = d/V$$

where d is the spacing between the beams, and V is the average velocity
of the flow.

5   **[0023]**   The signals from photodetectors 20a and 20b may be
filtered by band-pass filters, as described below, to isolate components
of the signals at different frequencies which are generated by different
flow components. The time delay τ is different for different flow
components. Miniature water droplets are moving with the speed of
10   water vapour whereas water aggregates are moving at much lower
speed, causing a slug effect. Example cross-correlation functions
corresponding to flow components 32, 34, 36 and 38/39 described
above are illustrated in Figure 5. In the Figure 5 example, the elapsed
time for miniature, medium and large droplets, and water aggregates is
15   20, 30, 46 and 70 μs, respectively. These time delays correspond to
average velocities V of 50, 33, 22 and 14 m/s for flow components 32,
34, 36 and 38/39 respectively, for spacing $d = 1.0$mm.

[0024]   Figure 6 illustrates another embodiment of the invention
20   wherein an additional pair of beams 62 and 64 generated by another
illuminator 66 are delivered through a window 68 into pipe 16 in the
vertical direction. Beams 62 and 64 are coupled with a second
collecting optical system (not shown in Figure 6) located underneath the
pipe in the same way as are beams 12 and 14 in Figure 1. In addition to
25   scattered and deflected light, the second collecting optical system
focuses beams 62 and 64 directly on a pair of photodetectors, thus,
providing the sensing of the beam attenuation in the water condensate 69
at the bottom of pipe 16. The attenuation is related to the depth h of the
water condensate 69 in accordance with Beer's law:

30 $$I = I_0 \exp(-ah)$$

where I_0 is the intensity of the beam without any water condensate, I is the measured intensity of the beam, and a is the extinction coefficient. The cross-sectional area A of water condensate in pipe 16 is related to depth h as

5

$$A = R^2 \arccos(1-h/R) - (R - h)(2Rh - h^2)^{1/2}$$

where R is the radius of the pipe. The flow rate of the water condensate F_{cond} may be calculated by multiplying this area by the velocity of the water condensate:

$$F_{cond} = AV_{cond}$$

10

[0025]   Collection of the deflected and scattered light from a shallow angle along a beam spanning pipe 16 causes integration of the signal because the flow velocity varies across the section of pipe 16. Therefore, according to yet another embodiment of the present invention

15   shown in Figure 7, in addition to integral evaluation of the average velocity profile, the flow is analyzed at a local measuring zone 70. Light beams 72 and 74 scattered by water droplets at a near perpendicular angle are collected with an optical system 76 into a photodetector unit 78 comprising a pair of photodetectors. The

20   measuring zone 70 can be located at various locations across pipe 16. An example of four measuring zones along the diameter of pipe 16 is shown in Figure 8. Zones could be located at various distances a from the center of the pipe. One of the preferable distances is $a = 3/4\ R$. Local flow velocity measured at this location is the closest to the

25   average velocity in pipe 16 with practically no effect from the flow profile.

[0026]   Multiple point flow measurement can be simplified if a transparent section 89 is mounted into pipe 16. This section may

30   represent a section of a glass pipe having the same internal diameter as pipe 16. Multiple point measurement could be achieved by using a

multi-focal optical system such as one shown in Figure 9. The optical system 110 consists of several optical components of various apertures, therefore, the optical power of the system varies with the number of components. In the example of Figure 9, four measuring zones 112,

5   114, 116 and 118 are associated optically with four photodetectors 122 , 124, 126 and 128, respectively, which measure scattered and deflected light from the measurement zones.

[0027]   Scattered and deflected light can also be collected in a
10   back-scattered mode as is shown in Figure 10. Photodetectors 132, 134, 136 and 138 measure scattered and deflected light from measuring zones 118, 116, 114 and 112, respectively, by means of a multi-focal optical system 130. The advantage of the back-scattering mode is the lower amount of background noise coming from the light scattered on
15   pipe walls because the light being registered has been scattered under high angles.

[0028]   Figure 11 schematically illustrates a signal processing means according to one embodiment of the invention. Electrical signals
20   from photodetectors 140 and 142, which may be any pair of photodetectors spaced apart along the direction of flow, are amplified (amplifiers are not shown) and digitized in analog-to-digital converters 144 and 146. Preferably, digital signals further are processed by digital signal processor (DSP). The signals are filtered by digital band-pass
25   filters 150, 152, 154, 160, 162 and 164. The number of digital filters may vary depending on the number of fluid components to be discriminated, which, in turn, is determined by the desired accuracy. The filter frequency bandwidth is determined by the number of bands to be selected and maximum fluid velocity. For example, to discriminate
30   four-components of the steam flow with a maximum velocity of 50m/s,

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the preferable bandwidths are: $\Delta f_1 = 0$ to 10 Hz; $\Delta f_2 = 10$ to 100 Hz; $\Delta f_3 = 100$ Hz to 1 kHz; and, $\Delta f_4 = 1$ to 100 kHz.

[0029]   Cross-correlation functions are calculated for each pair of signals filtered with the same bandwidth using cross-correlation (CC) procedures 170, 172, 174. Time delay τ_i for each CC function is determined as a position of the CC maximum. Local velocities are calculated for each flow component using the ratio:

$$V_i = d/\tau_i$$

As described above, the fastest measured flow components are the miniature water droplets which move at the speed of the vapour fraction in pipe 16.

[0030]   In addition to the velocities, the amount of each of the flow components may be calculated from the intensities of the filtered frequency components of the signals. For example, low intensity fluctuations recorded at bandwidth $\Delta f_3 = 100$ to 1,000 Hz indicate that the amount of medium size droplets (size about a micron for saturated steam) is low. The signal intensity at each bandwidth I_i is representative of the amount of the liquid fraction of each flow component. The relationship between I_i and the amount of the corresponding flow components is preferably established by calibration in a regulated flow environment. The intensities are preferably found as signal dispersions

$$I_1 = \int_{\Delta f_1} (U_f)^2 df$$

$$I_2 = \int_{\Delta f_2} (U_f)^2 df$$

$$I_n = \int_{\Delta f_n} (U_f)^2 df$$

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where U_f is the spectral density of the signal, which represents the distribution of signal dispersion in frequency domain. The spectral density can be measured by using Fourier transforms or by any other known means.

5

[0031]   After calculating the velocities of the flow components and the intensities of the corresponding signals (which is indicative of the amount of the corresponding flow component) for each measuring zone or "channel", the final liquid (water) and gas (vapour) flow rates are

10   found as is shown in Figure 12. The number of channels depends on the number of pairs of beams illuminating the fluid flow and the number of measurement zones for each pair of beams. The time delay τ and intensity I are calculated for each of the n components for each of the m channels, and provided to a flow rate calculator 200. Flow rate

15   calculator 200 also receives as inputs pressure and temperature data and the level of condensate 69 in the bottom of pipe, as calculated from absorption data as described above.

[0032]   The vapour fraction is calculated from the fastest of the

20   n-flow components, which are the nth components when Δf_n is the highest frequency bandwidth, over all m channels as follows:

$$F_{vapour} = \sum_{i=1}^{m} I_{in} V_{in}$$

[0033]   The total of the liquid and vapour fractions is calculated as a sum over all flow components:

25

$$F_{total} = \sum_{j=1}^{n} \sum_{i=1}^{m} I_{ij} V_{ij}$$

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[0034]   The quality of steam may be determined by the ratio:

$$Q = \frac{Vapour(mass)}{Vapour(mass) + Water(mass)} = \frac{F_{vapour}}{F_{total}}$$

5

[0035]   The equations above are corrected by pressure and temperature factors. The liquid condensate may be taken into account by calculating the cross-section of the pipe filled with liquid at a level (depth) h based on the absorption measurement described above with
10   reference to Figure 6.

[0036]   The embodiments above can be accomplished by a variety of ways. Preferably, light emitting diodes (LED) are used in illuminators as light sources. In particular, green, red and near-infrared
15   LEDs are suitable for this application as they are matched well with readily available and sensitive Si-photodiodes, which may be used as photodetectors. UV and blue LED provide better scattering efficiency due to the shorter wavelength, however, this may lead to high background light scattered inside pipe 16 and on optical windows, in
20   particular. It is desirable to use fiber optic components in illuminating and collecting optics because the operating temperature for steam pipelines is too high for direct contact with light sources and photodetectors. Semiconductor lasers are more suitable for fiber optics because they provide high coupling efficiency to thin fibers. Intensive
25   laser beams (power ranging from 1 to 10 mW) can be delivered through the windows at long distances using inexpensive visible and near-infrared lasers. Liquid fractions in the flow effectively scatter and deflect the propagating light, which can be collected at the photodetectors. The amount of light collected by the optical system

such as the dark-field system shown in Figure 9, can reach 1 W in a 2-inch steam pipeline. Such light intensity provides the signal-to-noise ratio in excess of 104 in regular PIN photodiodes or avalanche photodiodes. Therefore, time delays can be measured with high

5 accuracy. The device and method described above provide good averaging of flow velocity across the pipe. This reduces the error caused by the uncertainty of the flow profile and flow profile skewing which is the major source of the inaccuracy for ultrasonic flow meters. The described method is not affected by shock or vibration because it is

10 not based on interference. Lastly, the present invention provides a robust and a reliable device, and a method, which are not affected by turbulence. As opposed to other non-invasive flow metering techniques, such as, for example, ultrasonic methods, the flow turbulence is used in the present invention for modulation of scattered and deflected light.

15 The modulation depth increases with the turbulence level.

[0037]   As will be apparent to those skilled in the art in the light of the foregoing disclosure, many alterations and modifications are possible in the practice of this invention without departing from the

20 spirit or scope thereof. For example, although the embodiment of Figure 1 described above employs two beams and four photodetectors, it is to be understood that more than two beams could be used and the cross-correlation functions could be applied to any two of the beams. Also, the signals could be measured by any number of photodetectors,

25 provided there is at least one photodetector for each beam. Accordingly, the scope of the invention is to be construed in accordance with the substance defined by the following claims.

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WHAT IS CLAIMED IS:

1.   A method for measuring the velocity of a multiphase fluid flowing
     in a pipe, the method comprising:

     (a)   directing a pair of collimated beams of light from an
           illuminator through the multiphase fluid by means of
           transparent portions of the pipe, said pair of collimated
           beams spaced apart in a direction of flow of the multiphase
           fluid by a predetermined distance;

     (b)   detecting scattered, deflected and attenuated light with a
           pair of photodetectors to produce a pair of signals, each of
           said pair of photodetectors associated with one of said pair
           of collimated beams;

     (c)   calculating a cross-correlation function between said pair of
           signals to determine a time delay between the signals; and,

     (d)   calculating the average velocity of the multiphase fluid by
           taking the ratio of the predetermined distance to the time
           delay.

2.   A method according to claim 1 further comprising passing the
     pair of signals through a plurality of band-pass filters to isolate a
     plurality of pairs of corresponding frequency components, each of
     the plurality of pairs of corresponding frequency components
     corresponding to one a plurality of flow components.

3.   A method according to claim 2 further comprising, for each of
     said plurality of pairs of corresponding frequency components:

     (a)   calculating a cross-correlation function between the pair of
           corresponding frequency components to determine a time
           delay between the corresponding frequency components;
           and,

(b)   calculating the velocity of the corresponding flow
       component by taking the ratio of the predetermined distance
       to the time delay between the corresponding frequency
       components.

4.   A method according to claim 3 further comprising determining an
      intensity of each of said pairs frequency components and
      calculating an amount of a corresponding one of said plurality of
      flow components from said intensity.

5.   A method according to claim 4 further comprising determining a
      flow rate of each of said plurality of flow components by
      multiplying the velocity of each flow component by the intensity
      of the corresponding pair of frequency components.

6.   A method according to claim 5 wherein a vapour fraction of said
      multiphase flow is calculated as a flow rate of a fastest one of said
      plurality of flow components.

7.   A method according to claim 6 further comprising determining a
      total flow rate of said multiphase flow by summing the flow rates
      of all of said plurality of flow components.

8.   A method according to claim 7 further comprising calculating a
      quality of the multiphase flow by taking a ratio of the vapour
      fraction to the total flow rate.

9.   An apparatus for measuring the velocity of a multiphase fluid
      flowing in a pipe, the apparatus comprising:
      (a)   an illuminator for generating a pair of collimated beams of
             light from and directing said beams through the multiphase

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fluid by means of transparent portions of the pipe, said pair
of collimated beams spaced apart in a direction of flow of
the multiphase fluid by a predetermined distance;

(b)   a pair of photodetectors positioned across the pipe from
said illuminator, each of said pair of photodetectors
optically associated with one of said pair of collimated
beams for detecting scattered, deflected and attenuated light
from the associated beam and generating a signal; and,

(c)   a signal processing means for processing the signals from
said pair of photodetectors and calculating cross-correlation
functions between the signals to determine a time delay,
and for calculating the velocity of the multiphase fluid by
taking a ratio of the predetermined distance to the time
delay.

10.   An apparatus according to claim 9 wherein said signal processing
means comprises a plurality of band-pass filters for isolating a
plurality of frequency components of each of the pair of signals.

11.   An apparatus according to claim 9 wherein said illuminator
comprises a first illuminator for generating a first pair of
collimated beams, and wherein said pair of photodetectors
comprises a first pair of photodetectors, the apparatus further
comprising:

(a)   a second illuminator for generating a second pair of
collimated beams of light from and directing said second
pair of beams through the multiphase fluid at an angle to
said pair of beams generated by said first illuminator; and,

(b)   a second pair of photodetectors positioned across the pipe
from said second illuminator, each of said second set pair
of photodetectors optically associated with one of said

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second pair of collimated beams for detecting scattered,
deflected and attenuated light from the associated beam and
generating a signal,

wherein said signals from said second pair of photodetectors are
5   processed by said signal processing means.

12.   An apparatus according to claim 11 wherein the angle is
perpendicular.

10   13.   An apparatus according to claim 9 further comprising at least one
optical system for focusing light scattered at a near perpendicular
angle from said pair of collimated beams from at least one
measurement zone onto at least one photodetector.

15   14.   An apparatus according to claim 9 further comprising a multi-
focal optical system for focusing light scattered at a shallow angle
from said pair of collimated beams from a plurality of
measurement zones onto a plurality of photodetectors.

20   15.   An apparatus according to claim 9 further comprising a multi-
focal optical system for focusing light scattered at a near 180
degree angle from said pair of collimated beams from a plurality
of measurement zones onto a plurality of photodetectors.

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Abstract of the Disclosure

The invention provides a method for measuring the velocity
of a multiphase fluid flowing in a pipe. The method comprises directing
5   at least two collimated beams of light from an illuminator through the
multiphase fluid by means of transparent portions of the pipe, the at
least two collimated beams spaced apart in a direction of flow of the
multiphase fluid by a predetermined distance; detecting scattered,
deflected and attenuated light with at least two photodetectors to produce
10   at least two signals, the at least two photodetectors associated with the at
least two collimated beams; calculating a cross-correlation function
between the at least two signals to determine a time delay between the
signals; and, calculating the average velocity of the multiphase fluid by
taking the ratio of the predetermined distance to the time delay.
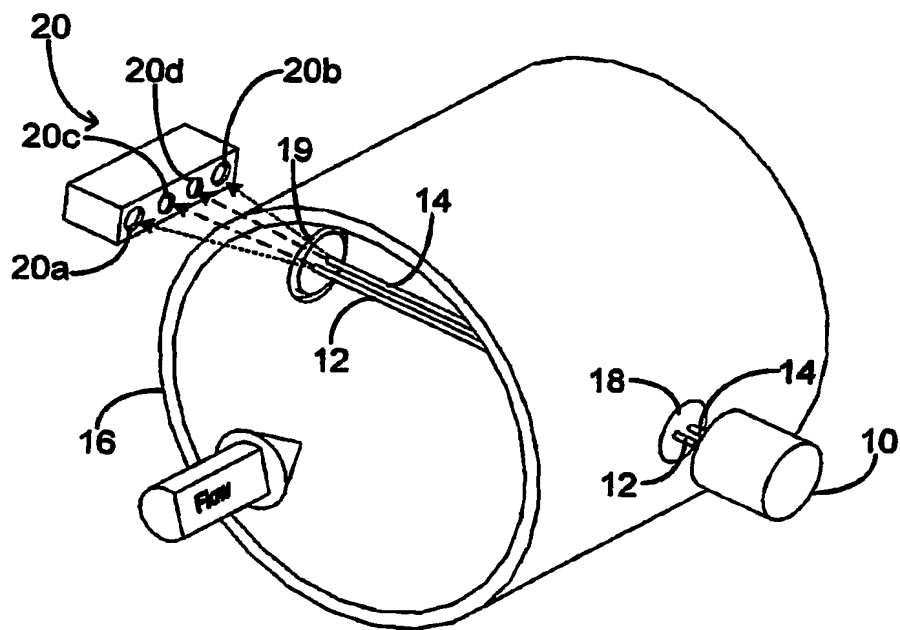
FIGURE 1

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FIGURE 2

FIGURE 3A

FIGURE 3B

Photodetector 2 , PD2
spaced at distance *d*

Photodetector 1, PD1

Time, t
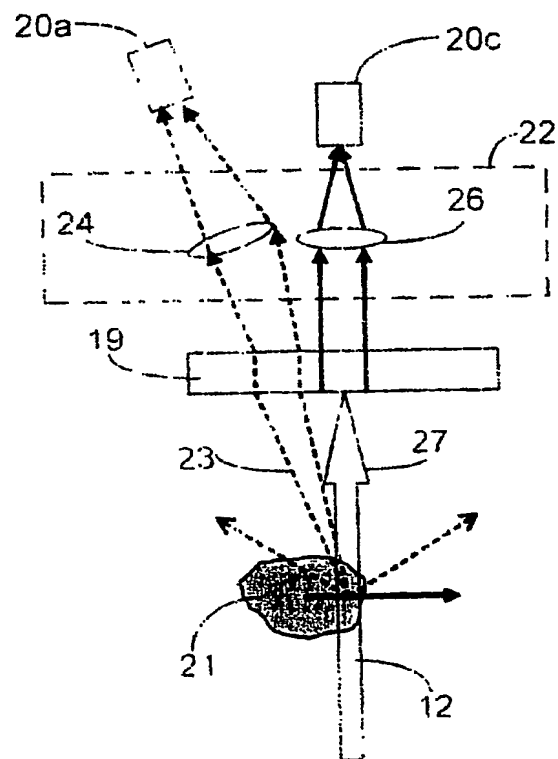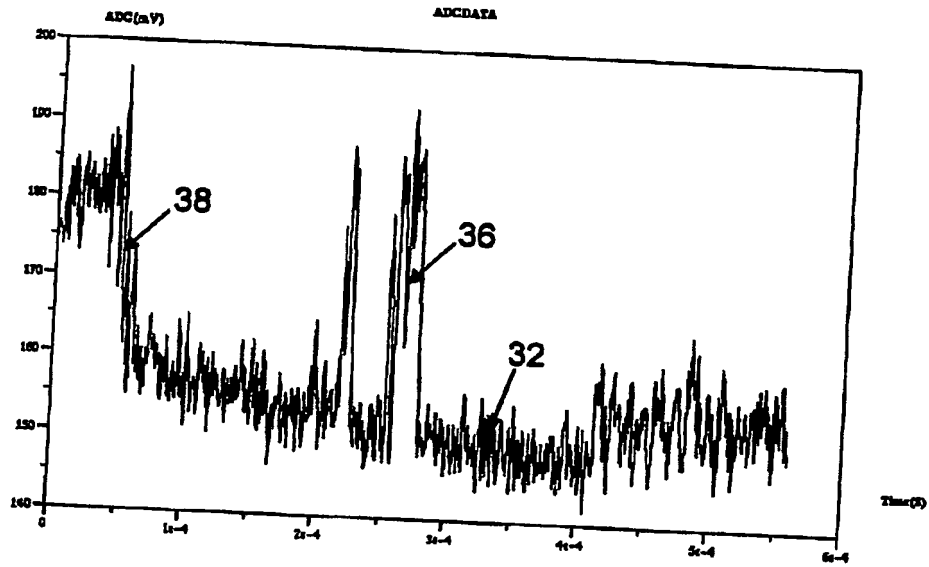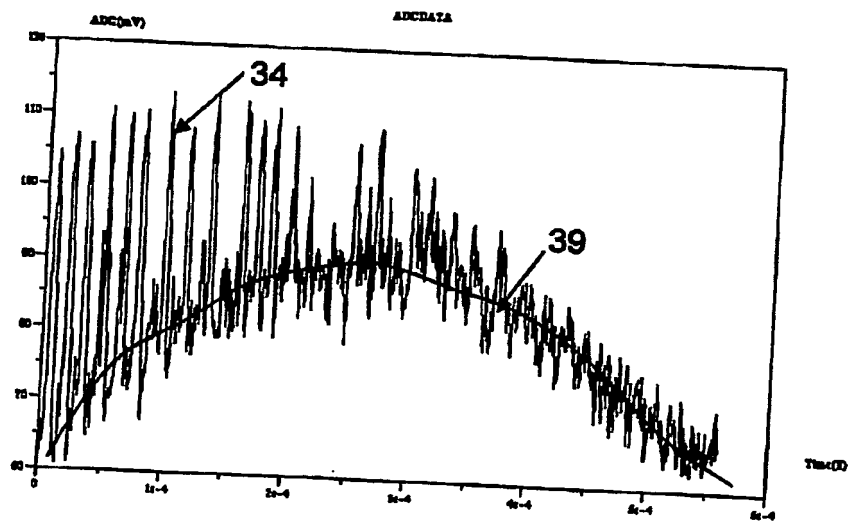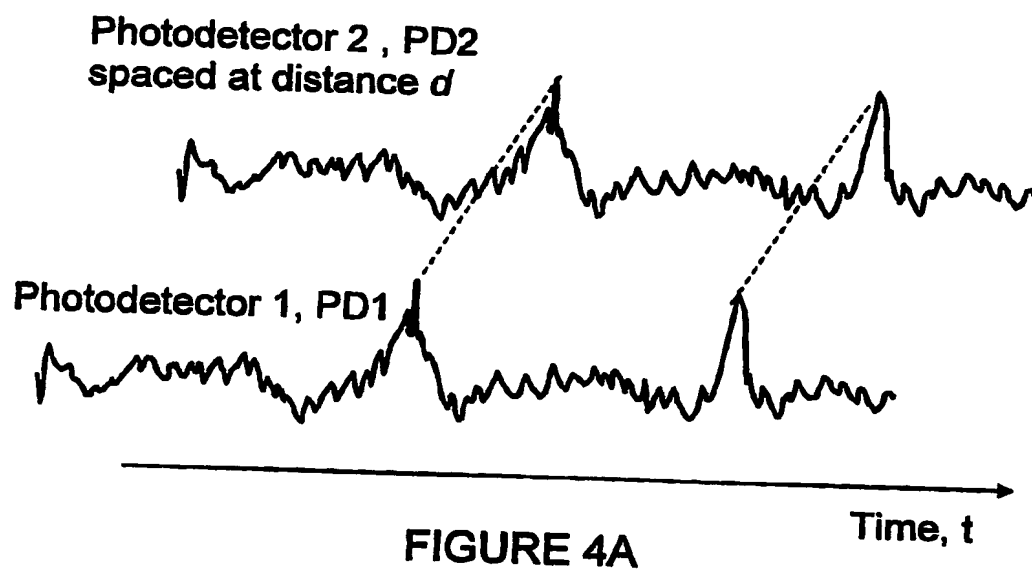
FIGURE 4A

Cross-correlation
PD1 & PD2
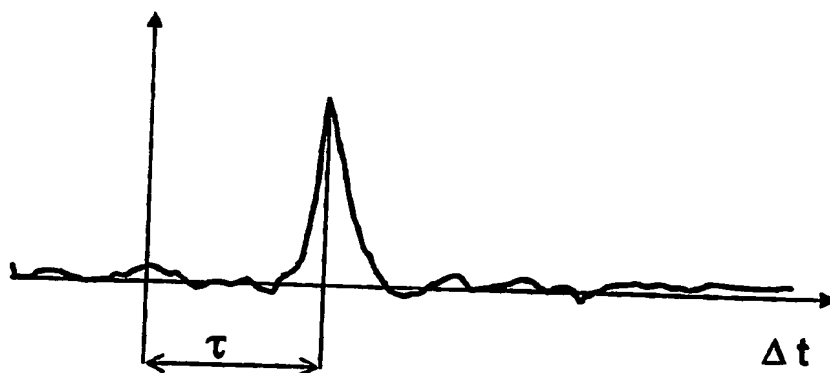
τ
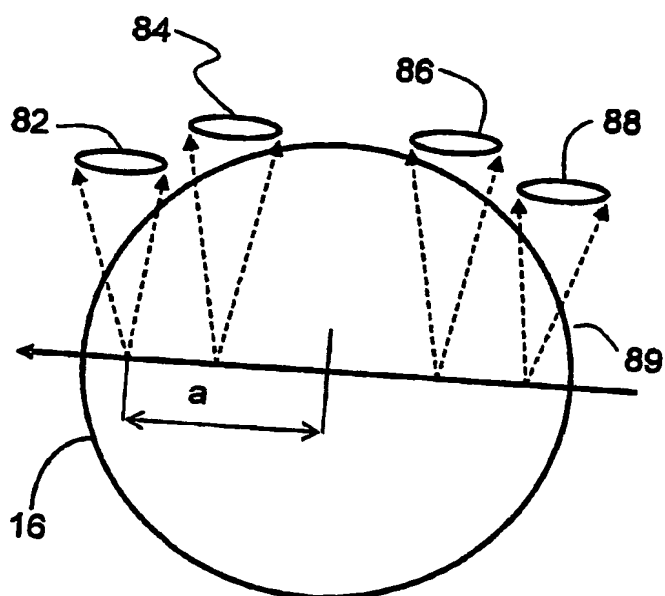
Δt
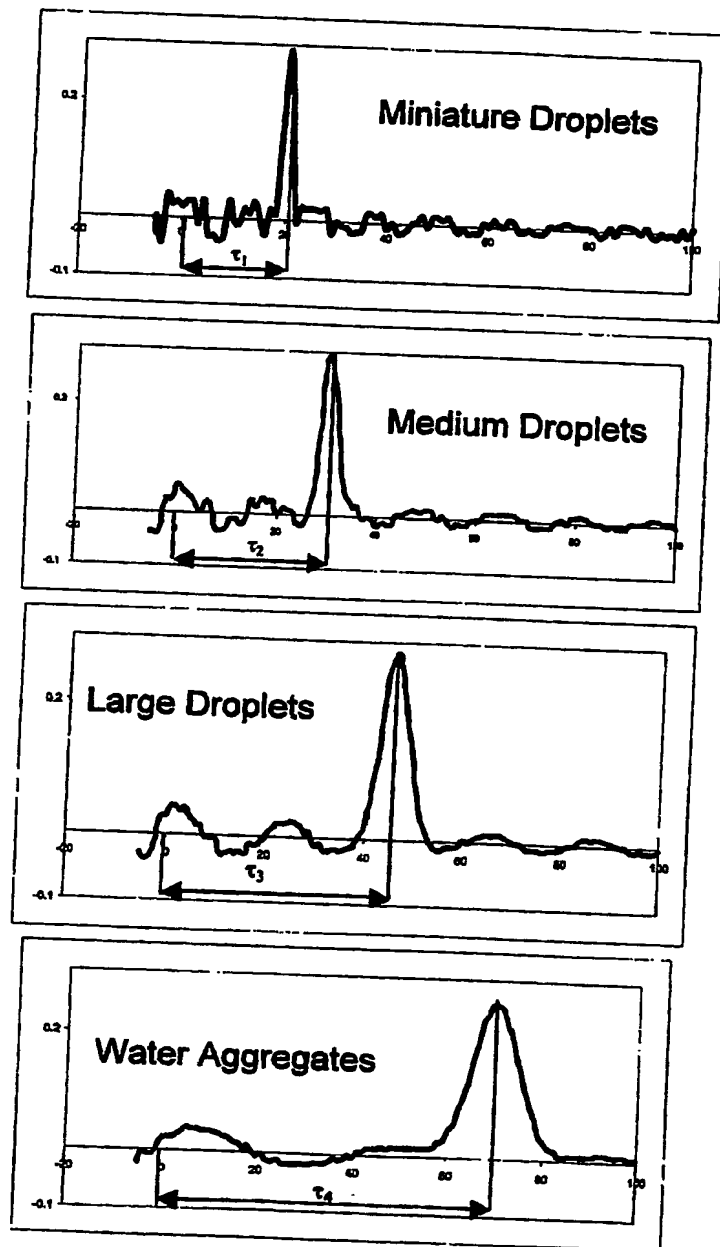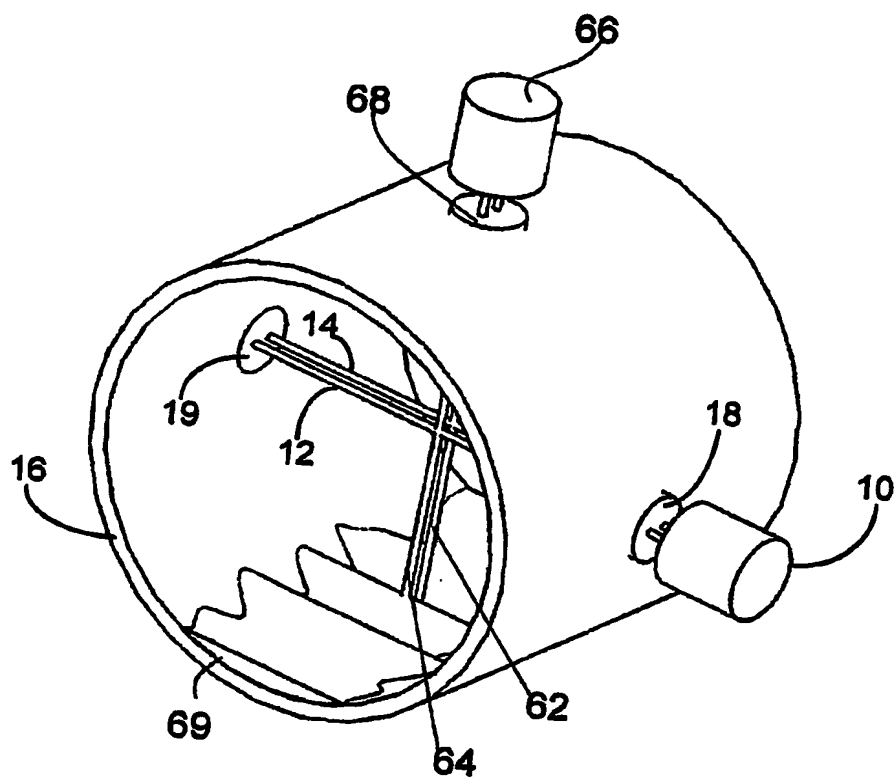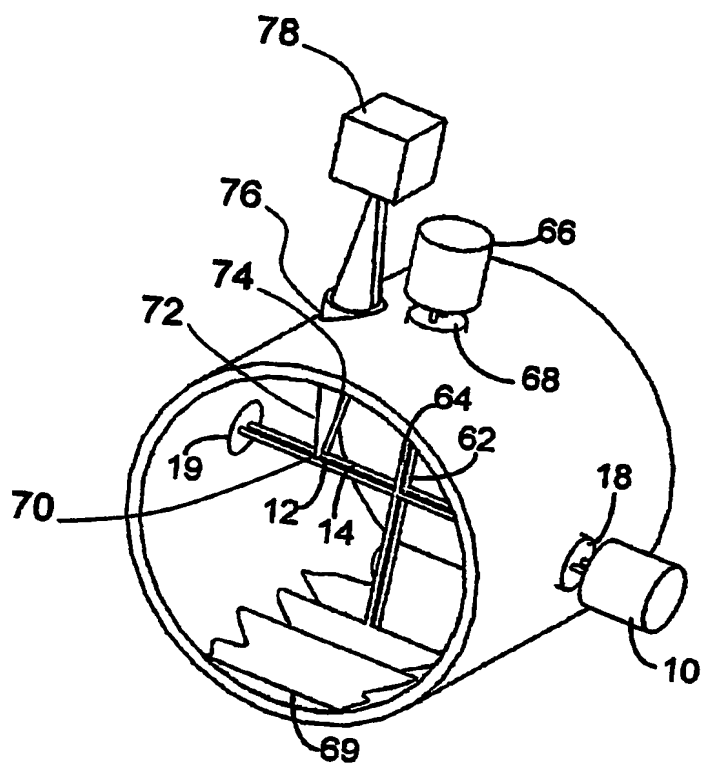
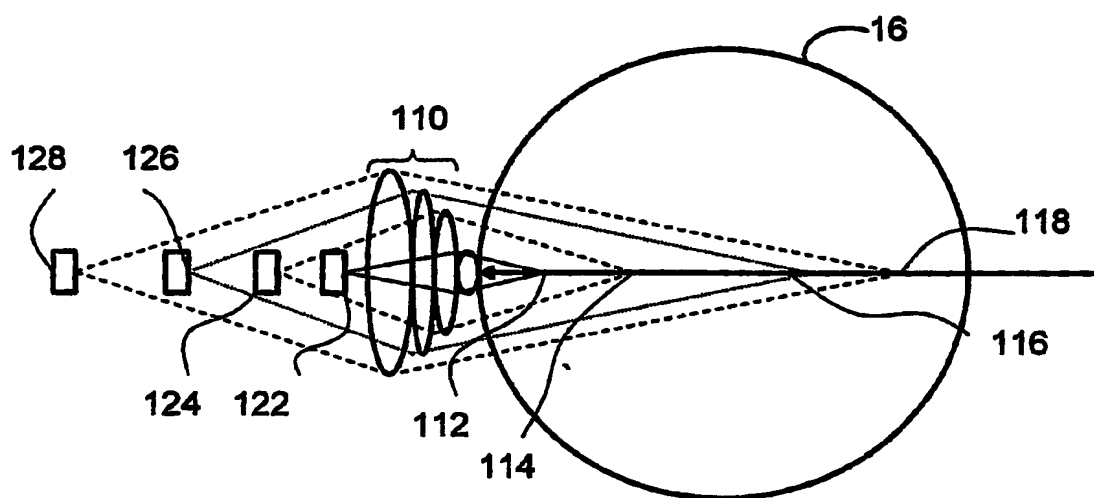**FIGURE 4B**

FIGURE 5

FIGURE 6
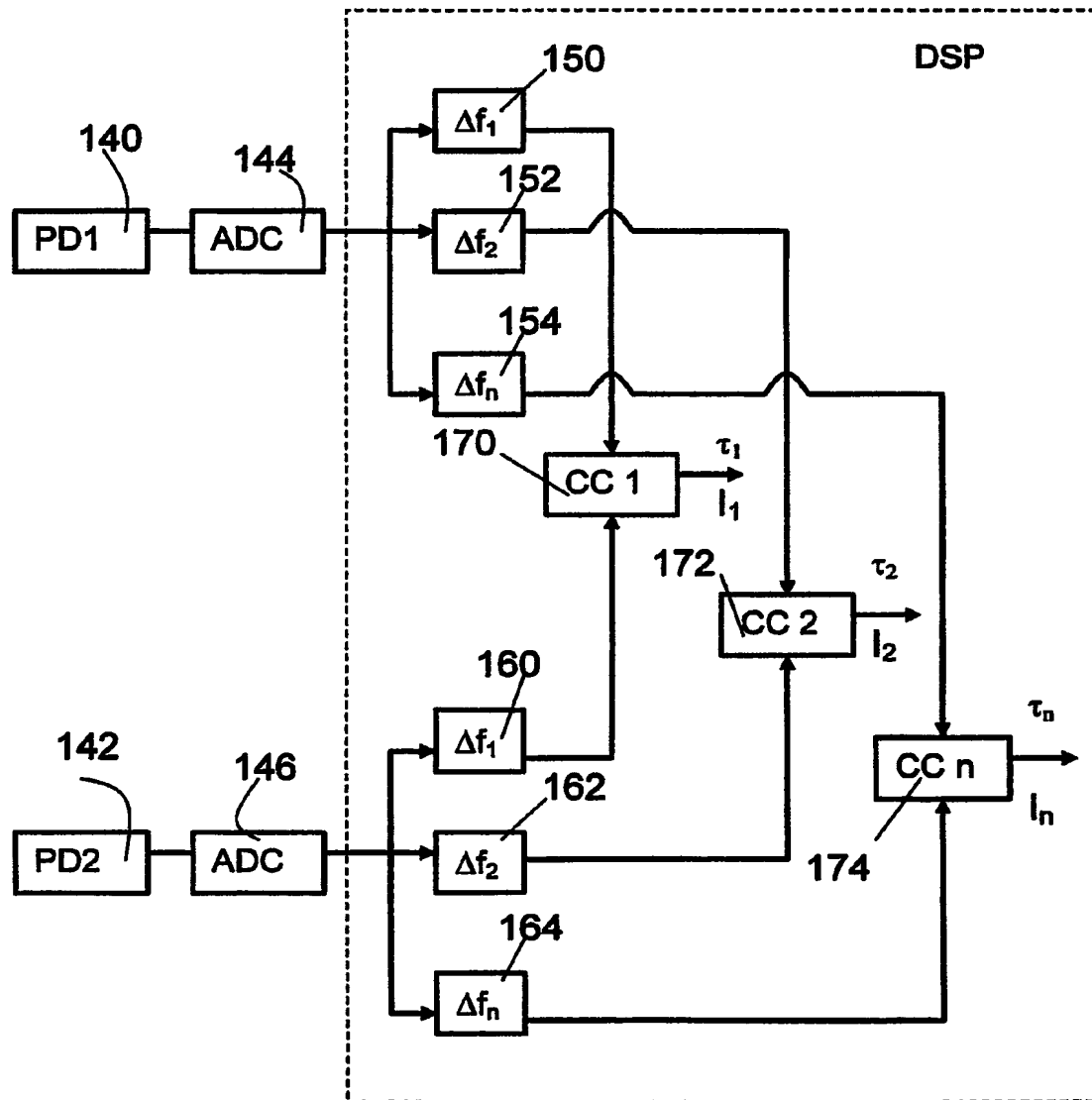
FIGURE 7

FIGURE 8

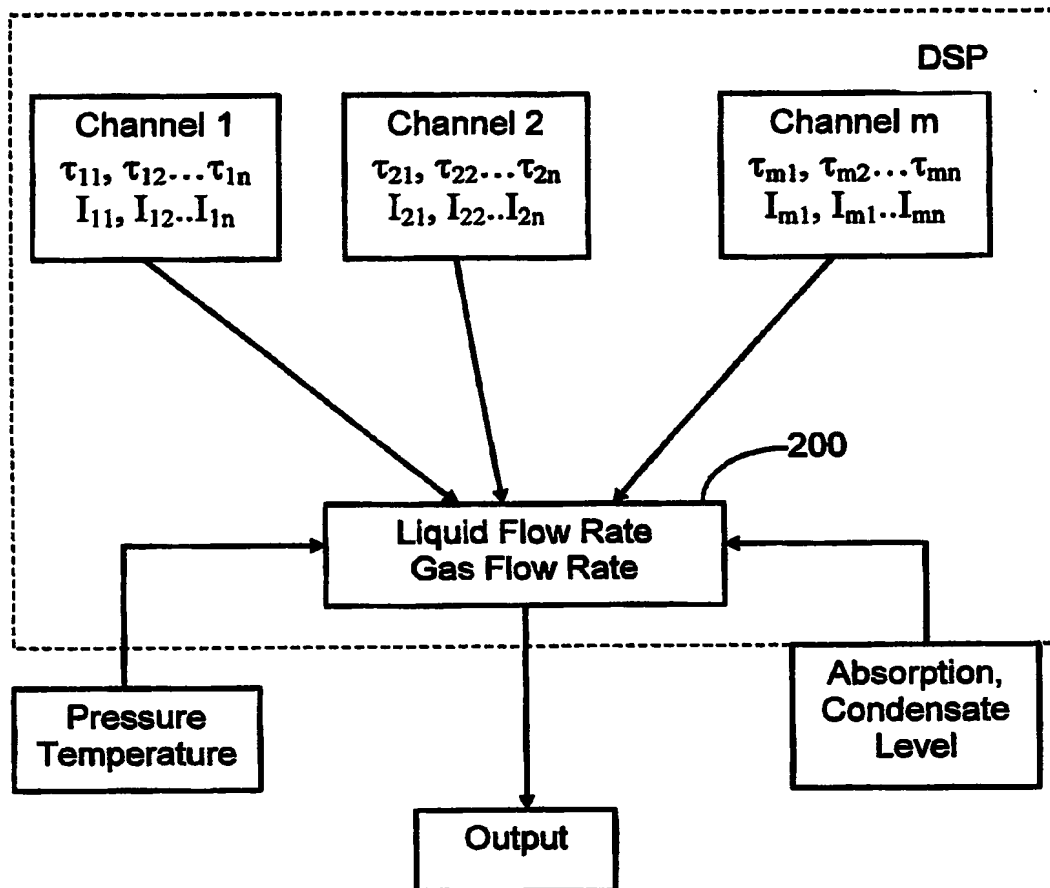FIGURE 9

FIGURE 11

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FIGURE 12

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